Open Journal of Geology, 2022, 12, 1093-1101
https://www.scirp.org/journal/ojg
ISSN Online: 2161-7589
ISSN Print: 2161-7570

Quantitative Characterization of Interlayer Interference in Multi-Layered Sandstone Reservoirs Offshore China

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How to cite this paper: Jin, X.W., Yang, L.H., Wu, D.H., Zhu, M.Y., Gao, S. and Jia, Y. (2022) Quantitative Characterization of Interlayer Interference in Multi-Layered Sandstone Reservoirs Offshore China. *Open Journal of Geology*, **12**, 1093-1101.
https://doi.org/10.4236/ojg.2022.1212051

Received: November 27, 2022
Accepted: December 25, 2022
Published: December 28, 2022

Abstract

X oilfield is a typical multi-layer sandstone reservoir in offshore China. In the early stage, in order to obtain economic oil production, directional well was used to adopt a set of multi-layer combined production, which resulted in serious interlayer interference, water injection inrush and low reserve utilization. Based on the theory of single-phase unstable seepage flow and the theory of oil-water two-phase non-piston displacement, the author innovatively established a mathematical model of interlayer dynamic interference in multilayer sandstone reservoirs, revealed the influence law of main controlling factors such as permeability, viscosity, starting pressure gradient and reservoir type on interlayer interference, and innovatively formed a quantitative characterization theory of interlayer interference in multilayer combined oil production. The technical demarcation of offshore multi-zone combined oil production reservoir system is formulated and the recombination of oil field development system is guided.

Keywords

Multi-Zone Sandstone Reservoir, Interlayer Interference, Single-Phase Unstable Seepage, Two-Phase Non-Piston Displacement

1. Introduction

At present, domestic and foreign research methods on inter-zonal interference mainly include laboratory experiment, numerical simulation, field test, field statistics and other methods [1]-[12], but all of them focus on a specific period of oilfield development, and there are few studies on different types of inter-zonal interference in different stages of development. X oilfield is characterized by thin inter-bed development, strong vertical heterogeneity, and large differences in reservoir types. After the middle and high water cut period, water flooding heterogeneity between layers is not only reflected in the dynamic and static contradictions of connected reservoirs, but also in the connectivity differences of different reservoir types. By using the method of reservoir engineering evaluation of interference coefficient, the author systematically analyzes the interlayer interference of X oilfield, and forms the interference coefficient evaluation chart of X oilfield. Based on the characteristics of thin inter-bed reservoir, the Buckley-Leverett theory was used to establish the theoretical model of multi-layer water flooding development, study the water flooding sweep coefficient and water flooding development index of multi-layer combined production reservoir under different thin inter-bed difference, permeability difference, viscosity difference and pressure difference, and compare the development effects of combined production and split production in X oilfield. The technical boundary of strata division in X oilfield is proposed.

2. Quantitative Characterization of Interlayer Interference in Multilayer Sandstone Reservoir

Based on the actual oilfield situation, the interference in the development process is divided into three modes: 1) the interference caused by the difference of permeability between layers; 2) interference caused by pressure imbalance between layers; 3) interference caused by different distribution range of longitudinal reservoir.

Mode 1: Interference due to interlayer permeability differences

1) The initial disturbance coefficient is derived from the unsteady seepage theory

It is assumed that there is a two-layer combined oil reservoir model, the original formation pressure of each layer is the same, there is no channeling flow between layers, and the boundary condition is infinite formation. The oil well is in the unstable seepage stage at the early stage of production, so under the condition of fixed production, the bottom hole pressure of the two layers at any time is the same, and the following relationship can be satisfied:

$$P_{wf}\left(t\right) = P_i - \frac{Q_1\left(t\right)\cdot\mu_{o1}}{4\pi k_1 h_1}\ln\frac{2.25\eta_1 t}{r_w^2} \tag{1}$$

$$P_{wf}\left(t\right) = P_i - \frac{Q_2\left(t\right)\cdot\mu_{o2}}{4\pi k_2 h_2}\ln\frac{2.25\eta_2 t}{r_w^2} \tag{2}$$

$$Q = Q_1 + Q_2 \tag{3}$$

$P_{wf}\left(t\right)$ is bottom-hole pressure at any time, MPa; P_i is original formation pressure, MPa; $Q_1\left(t\right)$ and $Q_2\left(t\right)$ are the oil production of the first layer and the second layer at any time, cm^3/s; μ_{o1} and μ_{o2} are the oil viscosity of the first and second layer, mPa·s; k_1 and k_2 are the permeability of the first layer and second layer, D; h_1 and h_2 are the thickness of the first layer and second layer, cm; η_1 and η_2 are the formation conductivity coefficient of the first layer and second layer, cm^2/s; t is time of production, s; r_w is radius of wellbore, cm; Q is combined oil production, cm^3/s.

If each layer is produced at a variable rate, the following relationship should be used to calculate the bottom hole pressure drop:

$$\Delta P = \frac{\mu_1}{4\pi k_1 h_1} \cdot \left\{ \sum_{i=1}^{n} \left[Q_1(t_i) - Q_1(t_{i-1}) \right] \ln \frac{2.25\eta_1 \cdot (t - t_i)}{r_w^2} \right\} \tag{4}$$

$$\Delta P = \frac{\mu_2}{4\pi k_2 h_2} \cdot \left\{ \sum_{i=1}^{n} \left[Q_2(t_i) - Q_2(t_{i-1}) \right] \ln \frac{2.25\eta_2 \cdot (t - t_i)}{r_w^2} \right\} \tag{5}$$

The oil production and bottom-hole pressure of each layer can be calculated by coupling the above types together

2) The late interference degree was deduced by the theory of oil-water two-phase steady seepage flow

It is assumed that there is no inter-layer channeling, rock and fluid are incompressible, water injection is equal to liquid production, and there is only oil-phase flow before the water flooding front, followed by oil-water two-phase flow. The oil well is produced with a fixed amount of liquid, and the water injection well is injected with a fixed flow pressure at the bottom of the well. The production pressure difference of each layer is the same at any time, so the liquid production of each layer meets the following equation before the first layer water:

$$Q_1 = \frac{k_1 A_1 \Delta P}{\int_0^{x_{f1}} \frac{1}{\frac{k_{ro1}}{\mu_{o1}} + \frac{k_{rw1}}{\mu_{w1}}} \mathrm{d}x + \mu_{o1}\left(L - x_{f1}\right)} \tag{6}$$

$$Q_2 = \frac{k_2 A_2 \Delta P}{\int_0^{x_{f2}} \frac{1}{\frac{k_{ro2}}{\mu_{o2}} + \frac{k_{rw2}}{\mu_{w2}}} \mathrm{d}x + \mu_{o2}\left(L - x_{f2}\right)} \tag{7}$$

Q_1 and Q_2 are the liquid production of the first layer and the second layer, m^3/d; A_1 and A_2 are the cross sectional area of seepage of the first layer and the second layer, m^2; ΔP is production pressure difference at any time, MPa; x_{f1} and x_{f2} are the water drive front arrival distance of the first and second layer, m; k_{ro1} and k_{ro2} are the oil phase relative permeability of the first and second layer, dimensionless; k_{rw1} and k_{rw2} are the water phase relative permeability of the first and second layer, dimensionless; μ_{w1} and μ_{w2} are the formation water viscosity of the first and second layer, mPa·s; L is the injection-production well spacing, m.

After water is seen in each layer, the movement equation of iso-saturated surface in the layer i is:

$$x_i = \frac{f'_{iw}(s_w)}{\phi_i A_i}\int_0^t Q_i \mathrm{d}t \tag{8}$$

$f'_{iw}(s_w)$ is derivative of water content corresponding to arbitrary water saturation in layer *i*, dimensionless.

The derivative of water content and the oil production at the outlet of the layer *i* are respectively:

$$f'_{iw}(s_{we}) = \frac{L\phi_i A_i}{\int_0^t Q_i \mathrm{d}t} \tag{9}$$

$$Q_{oi} = Q_i \times f_{iw}(s_{we}) \tag{10}$$

According to the above formula, the accumulative oil production and recovery degree of low permeability layer can be calculated at a certain time.

Mode 2: Interference caused by pressure imbalance between layers

It is assumed that there is a two-layer combined oil reservoir model, each layer has different original formation pressure, there is no channeling flow between layers, channeling flow only occurs in the wellbore, and the boundary condition is infinite formation. When the oil well is in the unstable seepage stage at the early stage of production, the bottom-hole flow pressure at any time under the condition of fixed production meets the following equation:

$$P_{wf}(t) = P_{1i} - \frac{Q_1(t)\cdot\mu_{o1}}{4\pi k_1 h_1}\ln\frac{2.25\eta_1 t}{r_w^2} \tag{11}$$

$$P_{wf}(t) = P_{2i} - \frac{Q_2(t)\cdot\mu_{o2}}{4\pi k_2 h_2}\ln\frac{2.25\eta_2 t}{r_w^2} \tag{12}$$

$$Q = Q_1 + Q_2 \tag{13}$$

P_{1i} and P_{2i} are the original formation pressure of the first layer and the second layer, 10^{-1} MPa.

If the production is carried out in the way of variable production, then Formulas (4), (5), (11), (12) and (13) are combined to solve the oil production of the two zones coupled, and the oil production of single zone and bottom-hole pressure at any time can be calculated.

Mode 3: Interference caused by different longitudinal reservoir distribution ranges

There are I, II and III types of reservoirs in X oilfield longitudinally. Due to the difference of injection-production relationship, the seepage law of different types of reservoirs is quite different. It is assumed that there is a two-layer reservoir model with the same original formation pressure in each layer but different corresponding relationship between injection and production. The boundary conditions of the first layer are infinite strata. The second layer has no energy supply and the boundary conditions are circular closed boundary. There is no channeling between layers, channeling only occurs in the wellbore, and the well is produced at a fixed rate. The oil well is in the unstable seepage stage at the early stage of production, and the bottom-hole flow pressure at any time meets the following equation:

$$P_{wf}(t) = P_i - \frac{Q_1(t)\cdot\mu_{o1}}{4\pi k_1 h_1}\ln\frac{2.25\eta_1 t}{r_w^2} \tag{14}$$

$$P_{wf}(t) = P_i - \frac{Q_2(t)\cdot\mu_{o2}}{2\pi k_2 h_2}\left\{\ln\frac{r_e}{r_w} - \frac{3}{4} + \frac{2\eta_2 t}{r_e^2} - 0.84\exp\left(-\frac{14.682\eta_2 t}{r_e^2}\right)\right\} \tag{15}$$

$$Q = Q_1 + Q_2 \tag{16}$$

By combining all the above methods and introducing the variable production pressure drop formula to solve the oil production of the two layers, the oil production of each small layer and the bottom hole pressure at any time can be calculated.

3. Effect of Application

Combined with the actual geological reservoir conditions of X oilfield, the relevant production parameters can be substituted into the formula to calculate the interlayer interference coefficient under the three modes

Mode 1: Interference due to interlayer permeability differences

Figure 1(a) shows that the difference in zonal permeability does not cause zonal interference during the early stage of well production, *i.e.*, the unstable seepage phase. Figure 1(b) shows that the high permeability layer will interfere with the low permeability layer in the stable oil-water two-phase seepage stage. This is because the water flooding front of the high permeability layer advances faster, the seepage resistance drops faster than that of the low permeability layer, and the liquid volume rises faster in the high permeability layer under the same production pressure difference. Figure 2 shows that the greater the permeability difference between layers, the higher the interference degree of low permeability layer.

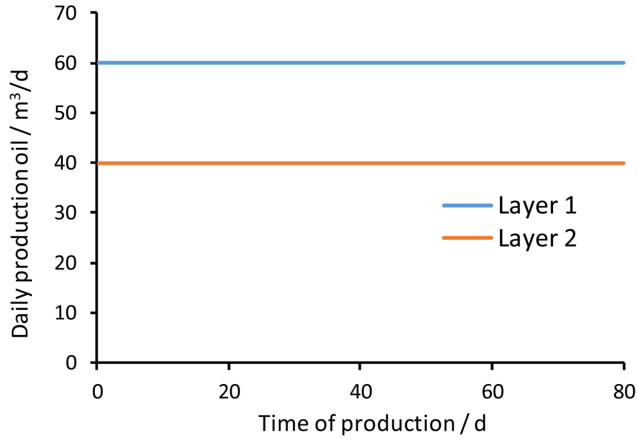
Mode 2: Interference caused by pressure imbalance between layers

Figure 3 shows that the greater the inter-layer pressure difference is, the larger the interference coefficient is. The amplification of production pressure difference can reduce the inter-layer interference.

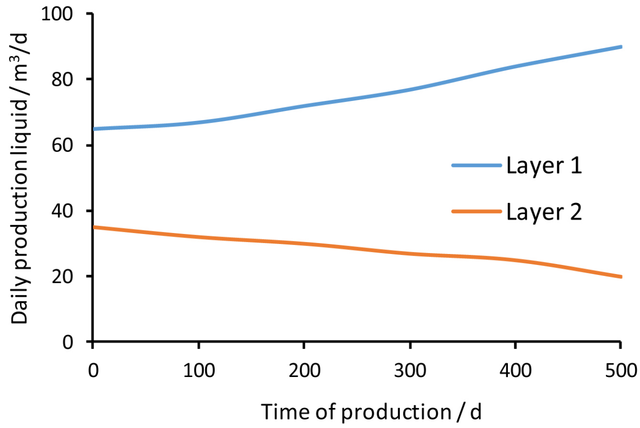
Mode 3: Interference caused by different longitudinal reservoir distribution ranges

As can be seen from Figure 4, as the thickness of the unconnected reservoir increases, the interference coefficient increases. Therefore, improving the injection-production correspondence of class II and III reservoirs is the key to reduce this kind of interlayer interference.

By substituting the relevant parameters of new Wells in X oilfield into the interference coefficient formula, the specific oil recovery index considering inter-zonal interference can be obtained (Table 1). The calculated value is close to the actual value, and the coincidence rate is up to 80%.



(a)



(b)

Figure 1. Variation law of liquid production in each layer with time under interference mode 1 (permeability difference is 2). (a) Unstable seepage stage; (b) oil-water two-phase seepage stage.

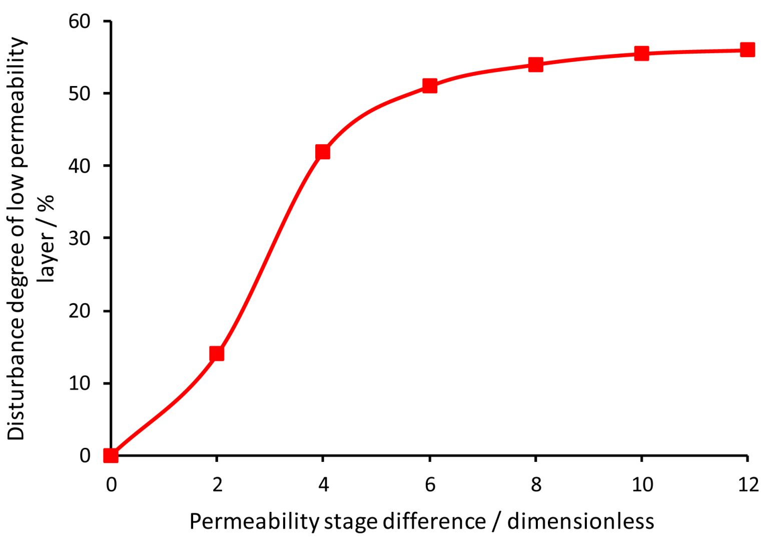


Figure 2. Variation law of the interference degree of low permeability layer with the permeability level difference.

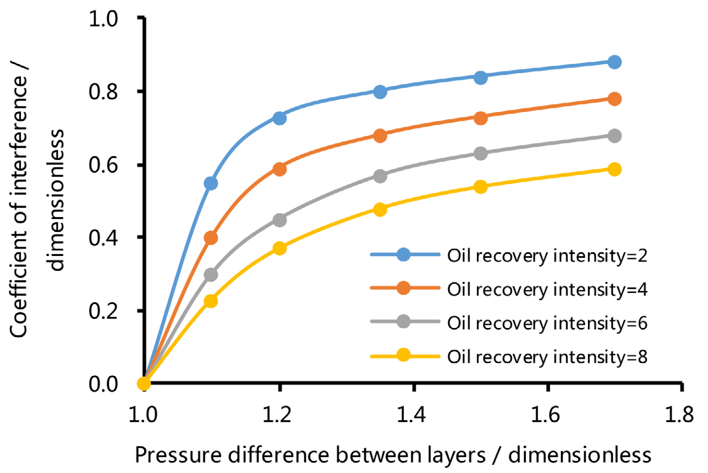


Figure 3. Variation law of interference coefficient with pressure difference between layers.

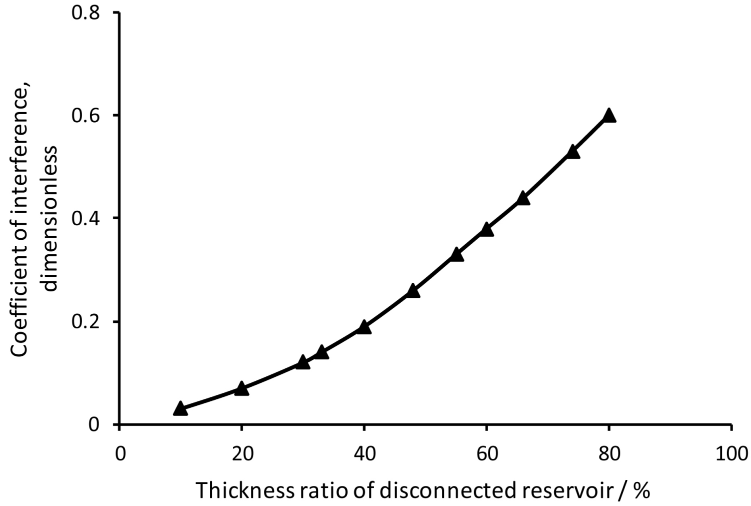


Figure 4. Variation law of interference coefficient with thickness ratio of unconnected reservoir.

Table 1. Calculation table of interference coefficient of new well in X oilfield.

Well	Theoretical specific oil recovery index $m^3/(MPa·d·m)$	Pressure difference between layers dimensionless	Inter-laminar pressure interference coefficient dimensionless	Calculate specific oil recovery index $m^3/(MPa·d·m)$	Actual specific oil recovery index $m^3/(MPa·d·m)$
A08S1	1.56	1.18	0.10	0.61	0.52
B08S1	2.86	1.16	0.09	0.92	1.02
C02S2	2.92	1.27	0.13	0.81	0.73
C40S1	1.26	1.11	0.06	0.48	0.45
E36S1	4.69	1.15	0.07	1.01	1.38
M16	2.09	1.36	0.15	0.53	0.51

4. Conclusions

1) Based on the actual geological reservoir characteristics of X oilfield, the quantitative characterization theory of interlayer interference in thin interlayer reservoir was innovatively established, the main controlling factors and interference mechanism of interlayer interference were analyzed, and the technical boundary for the division of offshore multi-layer combined oil production reservoirs was formed.

2) In the early stage of oil well production, that is, the unstable seepage stage, the difference of inter-zonal permeability will not cause inter-zonal interference. The high permeability layer will interfere with the low permeability layer in the stable oil-water two-phase seepage stage. The higher the permeability difference between layers, the higher the interference degree of low permeability layer.

3) The greater the inter-layer pressure difference is, the larger the interference coefficient is. The amplification of production pressure difference can reduce the inter-layer interference.

4) The larger the proportion of unconnected reservoir thickness is, the higher the interference coefficient will be. Improving the injection-production relationship of reservoirs with poor connectivity is the key to reducing inter-zonal interference.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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